THTEE-DIMENSIONAL STRESS AND DISPLACEMENT ANALYSIS OF YUTIAO CONCRETE FACED ROCKFILL DAM

Liu Xia
Linyi Institute of Water Conservancy Reconnaissance design of Shandong Provience, 276001,China

WU Xingzheng
China Institute of Water Resources and Hydropower Research, 100038, China
E-mail: wuxz[illegible]hr.com

Xin Junxia
Beijing Building Construction Research Institute, 100039, China

Tian Hangong
Linyi Institute of Water Conservancy Reconnaissance design of Shandong Provience, 276001,China

Abstract: Increasing the utilization ratio of quarry material at dam site is very important for saving cost and shortening construction schedule. It is of practical significance to evaluate and predict the behavior of dam by rational numerical analysis methods, especially to the site composed by soft rock, such as mudstone or shale rock.

Three-dimensional finite element analysis is performed using the selected material parameters to evaluate stresses and deformations of Yutiao concrete-faced rockfill dam during construction and reservoir-filling stages. The simple incremental elastic and isotropic hyperbolic model developed by Duncan and Chang is employed to characterize the inelastic deformation behavior of rockfill materials. A mid-point incrementally-iterative numerical technique is developed and incorporated into computer program which is able to simulate the non-linearity of rockfill materials in loading sequences during construction and reservoir-filling. The displacements and stresses of concrete slab and rockfills as well as deformations of peripheral joints are evaluated. Some conclusions can be drawn from this study.

The computed results of the present method are found to be in good agreement with those achieved by some engineering measured values. Some meaningful and insights are gained which are helpful to selections of rockfill materials and the basis for the engineering design of this dam.

Key words: Concrete-faced rockfill dam; stress; displacement; Finite-element-Method

1. INTRODUCTION

To develop hydroelectricity resource in southwest China and to accelerate economic development, many large hydroelectricity engineering are being constructed or will be constructed. Concrete-faced rockfill dam(CFRD) and core rockfill dam are adopted in some of them. For example, Pubugou core rockfill dam located at the Dadu River, Zipingpu concrete-faced rockfill dam located at the Minjiang River and Yutiao concrete-faced rockfill dam in Sichuan. These dams filled with soils and gravels have the following common characteristics. The first one is that there are unequal thickness overlying stratums in valley of dam base. Physical and mechanical characteristics of each soil along depth are obviously different, there are lenticular sand and soft soil in the stratum layer. The second one is that, shape of valley is complex. The left abutmet and the right one are asymmetric. The dip and the inclination are not equal. The effect of three-dimensional characteristics of canyon shape may be obvious. The third one is that the height of dam is from 100 to 200 meters, the slope of dam is about 1:1.4, the constituent materials are considerably complex. So there is a common problem whether the static response and stability of dam can meet the demand under complex valley condition with available soil and rockfill at dam site. This is a challenging topic.

Indoor tests and site surveys indicate that there is a great deal of mudstone at the site of Yutiao concrete-faced rockfill dam. Its average compression strength is 18.8MPa and its permeability coefficient is 3.65×10^{-2} cm/s. It has high degree of weathering and high content of fine particle. Whether this soft rock which can be used for the dam is an important problem. If stacking area far away from the dam is adopted, progress of works will be delayed and the investment will increase. In this paper, Three-dimensional stress and deformation analysis of the dam during construction and reservoir filling will be discussed in the following in order to systematically investigate the influence of mechanical characteristics of rockfill and canyon shape on stresses and deformations.

2. DAMPROFILE AND MATERIAL PARAMETERS

2.1 Dam profile

The height of Yutiao concrete-faced rockfill dam is 110.0m. The dam is located at canyon and karst region. The shape of valley is asymmetric. The slope of left abutment is 35°-50° and the one of right abutment is 55°～70°. The crest length is 204m, the crest width is 7m, and the aspect ratio is 1.855. The lowest elevation is 362.0m, the normal reservoir filling level is 463.57m, the design flood level is 467.0m, and the check flood level is 469.92m.

2.2 Material characteristics and correlated parameters

Stress and deformation analysis of earth and rockfill dams requires a reasonably accurate characterization of stress-strain relations of soil and rockfill materials. The simple incremental elastic and isotropic hyperbolic model developed by Duncan and Chang(1970) and Duncan et al. (1984), can directly capture the nonlinear behavior and pressure-dependency effects. Some parameters have definite physical meanings and their range can be obtained by collecting some testing data of Duncan J M et al, (1980), Zhu Baili, Shen zhujiang, (1990). E-B model proposed by Duncan Chang in 1980 can be divided into tangent modulus of elasticity, unloading modulus of elasticity and tangent modulus of volume, which includes eight constitutive parameters such as K_e, ϕ_0, $\Delta\phi$, R_f, n, K_b, m and K_{eur}.

Model parameters of rockfill in this study are shown in Table 1, according to the report of IWHR (2000). The parameter K_{eur} is obtained by triaxial unloading-reloading test by Huang Yipen et al, (1993) or measured at site by Byrne P M, Cheung H, Yan L (1987), Pai Shutian et al,(1999) and its value is three time as the one of corresponding loading modulus coefficient. The moduli of concrete-facing are obtained according to class C20.

Table 1 Model parameters of Duncan model

Type	K_e	ϕ_0 / (°)	$\Delta\phi$ / (°)	n	R_f	K_b	m
Slab	190000	0	0	0	0	120000	0
Main rockfill	800	46	0	0.34	0.75	400	0.40
Bedding	910	45	0	0.37	0.65	455	0.40
Transition	850	46	0	0.37	0.65	425	0.48
Secondary rockfill	300	42	5.7	0.17	0.82	166	0.28

3. ANALYSIS OF STRESS AND DEFORMATION OF THE DAM

3.1 Mesh discretization and loading steps

Different finite elements, such as slab elements, interface elements and peripheral joint elements, are utilized to duly consider special characteristics in geometrical configuration and material zoning of CFRDs. The isoperimetric element which has eight points is adopted in finite element mesh discretization. Using by midpoint incremental method non-liner deformation characteristics of soil are simulated during filling, reservoir filling loading. Therefore three-dimensional finite element analysis program of dam is coded.

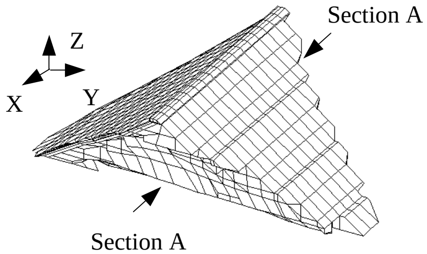


Fig. 1 Three-dimensional finite element discretization of Yutiao dam

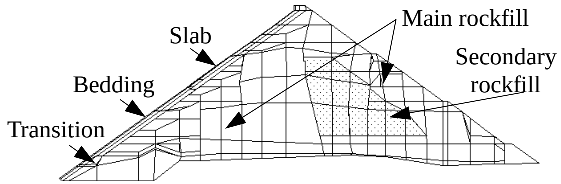


Fig. 2 Maximum cross section of the dam

Positive direction of X axis correspond to the direction from left abutment to right abutment, the one of Y axis correspond to the direction from upstream to downstream, and the one of Z axis is the direction from bottom to top. The total number of nodes is 2255 and the total number of elements is 1984 with 244 slab elements. The load step of construction of the dam is 12. The 13th step is casting slab. The 14th step is beginning to reservoir filling. The depth of reservoir filling is 108.0m in 17th step. The dam is divided into 17 sections along axial line of the dam. The three-dimensional finite element mesh discretization of dam is shown in Fig.1, and the section A is along the longitudinal direction. Fig.2 illustrates the maximum cross section of dam. The material type of dam is divided into 5 regions, that is impervious region, bedding region, transition region, main rockfill region and secondary rockfill region.

3.2 Results

3.2.1 Deformations and stresses of dam during construction

Deformation and stress of the maximum cross section

Contours of horizontal displacements and vertical displacements of the major cross section of the dam during construction are shown in Fig.3 and Fig.4, respectively. Fig.3 shows that the peak displacement in upstream-downstream direction of upstream slope is 34.0cm and the one of downstream is 47.0cm. The reason of asymmetry of displacements in upstream-downstream direction is the topographic change and difference of parameters of the material. It is shown in Fig.4 that the peak settlement of the dam is 82.0cm, which occurs at the right position of the cross section. The reason is that mechanical characteristics of secondary rockfill are lower than those of other regions. And the peak settlement of the homogeneous dam occurs in axial line, which is 0.61cm when only one type of main rockfill is used.

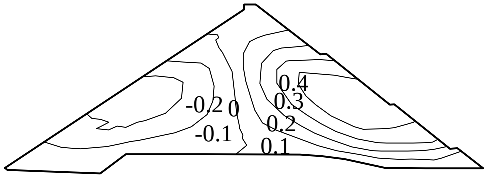


Fig. 3 Contours of horizontal displacements of the dam during construction (m)

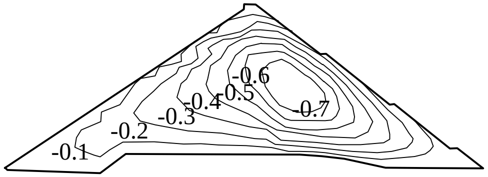


Fig. 4 Contours of vertical displacements of the dam during construction (m)

Contours of major principal stresses of the dam during construction are shown in Fig.5. It shows that major principal stress is 1.78 MPa, which occurs at the bottom of the dam. Contours of minor principal stresses of the dam during construction are shown in Fig.6. It shows that minor principal stress is 0.74 MPa, which occurs at the bottom of the dam.

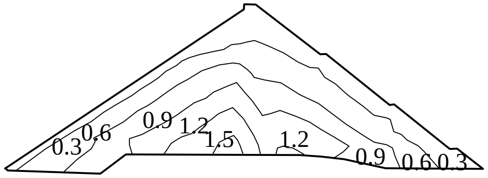


Fig. 5 Contours of major principal stresses of the dam during construction(MPa)

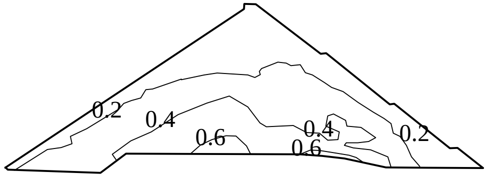
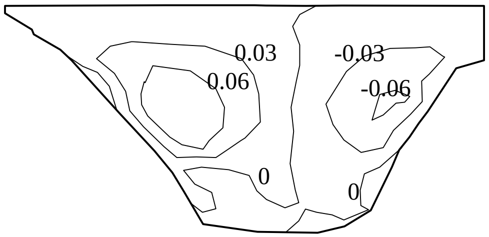


Fig. 6 Contours of minor principal stresses of the dam during construction (MPa)

Deformation of section A along the longitudinal direction

Contours of displacements in X direction and Y direction are shown in Fig.7 and Fig.8. Fig.7 shows that major displacement of left abutment is 0.072m and the one of right abutment is 0.063m. Fig.8 shows that major displacement in Y direction in axial line along the longitudinal section is 0.1m, which occurs at 2/3H.



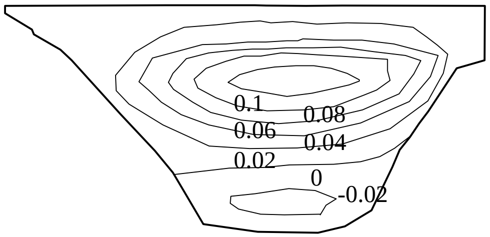


Fig. 7 Contours of displacements in the X direction of the dam along the longitudinal section (m)

Fig. 8 Contours of displacements in the Y direction of the dam along the longitudinal section (m)

3.2.2 Stresses and deformations of slab

Slab is under the condition of compression because of its self-weight during construction and major compression stress is 0.11 MPa. The major deformation of slab is 0.029cm, which occurs in the middle of slab.

3.2.3 Stresses and deformations of the dam during reservoir filling

a. Stresses and deformations of major cross section

Contours of horizontal displacements of the dam during reservoir filling are given in Fig.9. The peak deformation in upstream-downstream direction is 22.04cm. Compared with results of construction, it shows that the deformation of upstream during reservoir filling is less than that of construction and deformations of downstream under the two loading conditions are the same. Contours of settlements of the dam during reservoir filling are given in Fig.10 whose major value is 85.0cm. Comparison between Fig.3 and Fig.10 shows that the settlement increases slightly during reservoir filling. It can be seen that water loading has great influence on horizontal displacements of upstream slope and has little influence on horizontal displacements of downstream slope.

Contours of major principal stresses of the dam during reservoir filling are shown in Fig.11. It shows that major principal stress of the rockfill is 1.87Mpa and it is larger than that of construction, indicating increase of contours from the central region towards upstream. Contours of minor principal stresses of the dam during reservoir filling are shown in Fig.12. It shows that minor principal stress is also larger than that of construction.

In addition, Contours of the stress level of upstream during reservoir filling are lower than those obtained in construction phase. This is so because the major and minor principal stress increase due to application of reservoir load, but the increase of minor principal stress is greater than the increase in major principal stress, causing the shear stress to drop and the stress level to decrease.

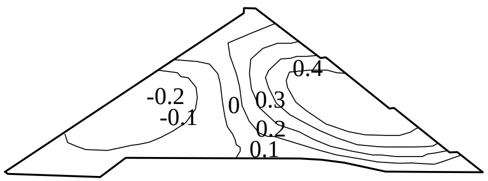


Fig. 9 Contours of displacements in the y direction of the dam for reservoir filling (m)

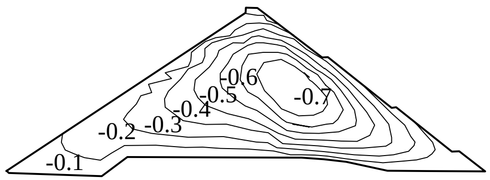


Fig. 10 Contours of displacements in the Z direction of the dam for reservoir filling (m)

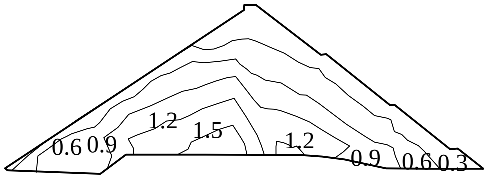


Fig. 11 Contours of major principal stresses of the dam during reservoir filling (MPa)

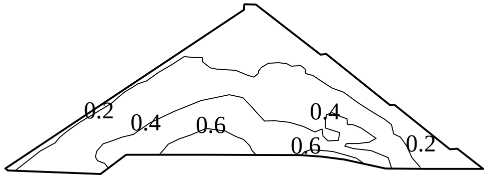


Fig. 12 Contours of minor principal stresses of the dam during reservoir filling (MPa)

b. Deformations of section A along the longitudinal direction

Displacements in X direction decrease slightly and those in Y direction and in Z direction increase 30%. So water loading has some influence on horizontal displacements in upstream-downstream direction in axial line of the dam.

3.2.4 Deformation and stress of slab during reservoir filling

Stresses and displacements of slab depend on deformations of rockfills. Contours of displacements of slab in X direction and Z direction during reservoir filling are shown in Fig.13 and Fig.14. Fig.13 shows that major horizontal displacement of slab in X direction occurs at 0.7～0.8H whose value is 0.035m. Fig.14 shows that major vertical displacement of slab occurs in the middle of slab whose value is -0.169m. Vertical displacements decrease gradually from middle of slab to the abutment.

Distribution of stresses of slab along the dam slope for reservoir filling is shown in Fig.15. It shows that major stress of compression along the dam slope is 2.29Mpa, which occurs at the lower side of the middle of slab. Distribution of stresses of slab in axial line for reservoir filling is shown in Fig.16. It shows that the middle of bed river slab is under the condition of compression and major stress of compression is 2.61Mpa. That occurs near the bottom of lower side of the middle portion of slab. Because of the restrain of abutment and rockfills, tension stress regions occur at dam abutments on the right one and the left one. The major tension stress of the right abutment is 1.36Mpa and the one of the left abutment is 0.67Mpa. The major tension stress of the steeper right abutment is larger than that of the left bank. Some engineering measures should be taken in order to prevent the tension stress of the slab from exceeding allowable value.

3.2.5 Displacements of peripheral joint of slab

Distribution of displacements of peripheral joint of slab can be obtained through three-dimensional finite element analysis, which can not be evaluated by two-dimensional finite element analysis. Displacements in X, Y and Z direction magnified for 2000 times are given in Fig.17(a), (b) and (c).

Maximum displacement in X direction occurs at the left bank whose value is 1.06cm and major displacement in X direction of the right bank is -0.59cm. Major displacement in Y and Z direction are 1.46cm and 1.31cm, respectively. Therefore watertight measures should be taken during construction.

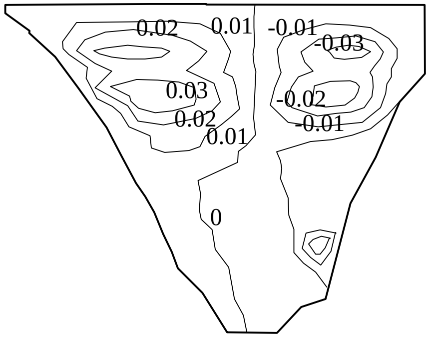


Fig. 13 Contours of displacements in the X direction direction

of the slab for reservoir filling (m)

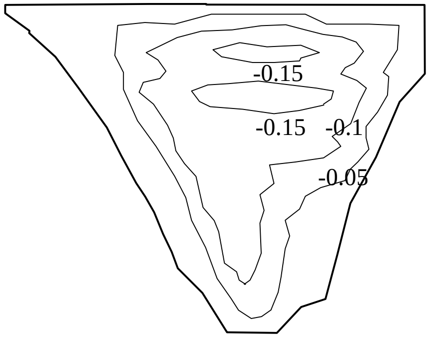


Fig. 14 Contours of displacements in the Z

of the slab reservoir filling (m)

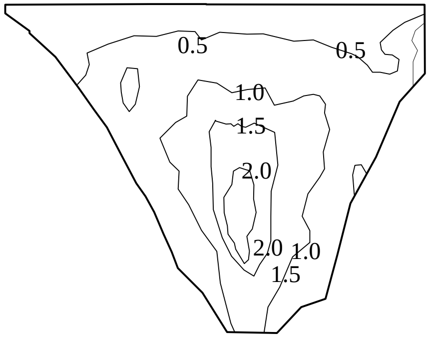


Fig. 15 Contours of stresses on slab in the direction

along the dam slope for reservoir filling (MPa)

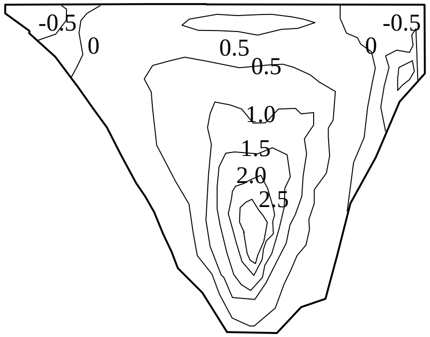
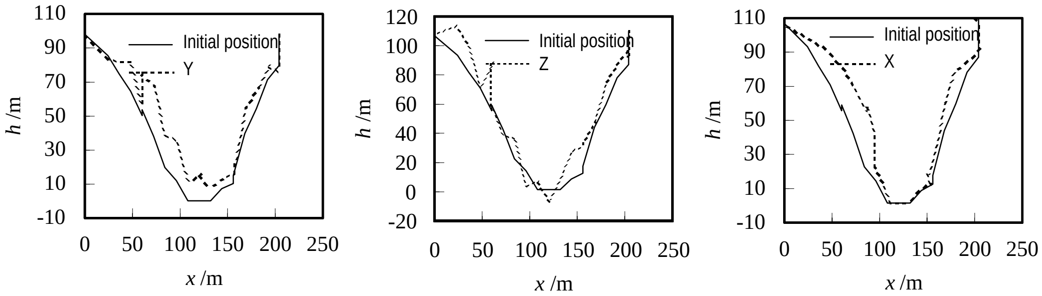


Fig. 16 Contours of stresses on slab in the direction

along the dam axial for reservoir filling (MPa)



(a) y direction (b) z direction (c) x direction

Fig. 17 Displacements of peripheral joints during reservoir filling

3.2.6 Sensibility analysis of model parameters

Referring to related literatures by En Fake,(1999) , Wu Xingzheng, (2001), model parameters, such as K_e 、n 、K_b 、m and K_{eur}, of rockfill are increased or decreased for 20% in present sensibility analysis. When the values of model parameters decrease, vertical displacement, horizontal displacement of the dam and settlement of slab all increase obviously. And stresses of slab also increase because of the decreasing of stiffness of dam body. Displacements of peripheral joint in three directions of slab increase for about 23%. Thus, leakage and crack would be occur for high concrete-faced rockfill dams. So it is important to control degree of compaction during construction and to strengthen the monitoring and controlling of displacements of downstream slope of rockfill and the slab.

4. CONCLUSIONS

Numerical results presented are instructive to gain better understanding on the response behavior of the dam body and the slab during construction and reservoir filling.

Settlement of the dam is as much as 1% of the dam height, which occurs in the middle of the dam. The major settlement is near downstream slope slightly. The existing of soft rock has not important impact on safety of the dam body and the facing slab. So the current design scheme is approximately feasible and most rockfill can be used. But monitoring of displacements of the dam during construction must be strengthened. The displacement of peripheral joints between slab and footwall is small with maximum absolute value of 2cm during reservoir filling, thus some special measures need not to be taken, but the choice of the type of watertight and joint sealing material should be considerate carefully. A few bearing reinforcements need to be set because tension stresses occur in some region of slab.

In addition, the effect of the three-dimensional characteristics of canyon shape on response of CFRD is discussed. The stresses and displacements obtained by the conventional two-dimensional analysis is larger because the loading transfer to the valley slope is not taken into account. The similar distribution pattern is gained by these two methods, but the three-dimensional analysis can achieve the relative reasonable computation results, especially in a narrow valley and local irregular topographical conditions.

ACKNOWLEDGMENTS

This study was supported by the Key Project of National Electric Power Corporation (SPKJ013-09).

REFERENCES

Byrne P M, Cheung H, Yan L, 1987. “Soil parameters for deformation analysis of sand masses”. Canadian Geotechnical Journal, 24, pp. 366-376.

Duncan J M, Byrne P, Wong K S, Mabry P, 1980. “Strength, stress-strain and bulk modulus parameters for finite element analysis of stress sand movements in soil masses”. In: Report No. UCB/GT/80-01, University of California, Berkerley.

Duncan J M, Chang C Y, 1970. “Nonlinear analysis of stress-strain for soils”. Journal of Soil Mechanics and Foundation Division, ASCE, 96(SM5), pp. 1629-1653.

Duncan J M, Seed R B, Wang K S, and Ozawa Y, 1984. FEADAM84: “A computer program for finite element analysis of dams”. Department of Civil Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

En Fake,1999. “Sensitivity analysis of material parameters of Rockfill dams”. Journal of Hehai University, Vol. 27, No.5, pp. 94-99.

Huang Yipen, Aheng Guang, Si Hongyang, Li Guofan, 1993. “Monitoring and performance of Xibeikou CFRD”. In: Proceeding of International Symposium on High Earth-Rockfill Dams (Sponsored by Chinese Society for Hydro-electric Engineering and International Commission on Large Dams), Beijing, pp. 475-482.

Institute of Water Resources and Hydropower Research of Chinese (IWHR), 2000. “Slope stability and 2D stress-strian analysis of Yutiao Concrete faced Rockfill Dam”. (NO. GE-2000-03-042).

Pai Shutian, Zhou Xiaoguang, Chao Huayi, 1999. “Influence of stress path on deformation characteristics of rockfill”. Journal of Hydropower of Chinese, No.4, pp. 76-80.

Wu Xingzheng. “Static and dynamic constitutive model of rockfill materials and applications in nonlinear analyses of high concrete-faced rockfill dams”. Dalian: Dalian university of technology, 2001.

Zhu Baili, Shen zhujiang. Soil mechanics of computation. Shanghai: Shanghai scientific and technical press, 1990.